NASA BIOSYSTEMS - BIO-OPTICS

This is a report on the work on bio-optics since the initial progress report. The first section of this chapter will deal with questions as to the application of liquid crystals to control problems. A later section will be concerned with the theoretical results for ellipsoidal particles representing long molecules in a simple shear field.

Applications

The application of liquid crystals proposed in the first report was centered around the control of the index of refraction of "eye glasses" to allow continuous focusing as substitute for bifocal or trifocal lenses now used for vision correction. The next extension would be to the augmentation of visual accommodation in dynamic tracking problems. Most tracking models of visual response have dealt with the motor control of the eye in following objects in a plane or essentially "far away". (i.e., the up-down and sidewise motion of the eye.) If one examines the reaction times of the important control processes in vision, however, the limiting response time is that of accommodation or focus control. The response time for eye movement is approximately 120 milliseconds, for pupil reaction 250 miliseconds, but for accommodation 400 milliseconds. The ability to maintain focus on an

object which is in motion toward and away from the observer appears to be the limiting function in eye control. (The 400 milliseconds response time is that recorded for a 2 diopter change in focus.[1])

The question remains as to what this effect has on our ability to track rapidly-approaching or receding objects. Possible consequences on man's ability to respond to rapidly changing visual events have not been explored.

As an example of the situations where control of accommodation may be important let us consider the response of the eye in tracking or observing an object which is viewed through a screen. The eye has great difficulty in focusing on the screen from a focus on a distant object. If the object is to be fixed in position on the grid, this is an oscillatory tracking maneuver difficult to maintain. It is known that in the adjustment in focus required to follow receding objects the eye may lose focus and instead of continuing to track may fluctuate about an intermediate focus. Another response is an oscillatory focus with with lens of the eye moving in the opposite direction from the object being tracked. All these effects or combinations may occur in the processes of visually observing a sequence of near and distant objects. If the human physiological focus control is not adequate for these type tasks an augmentation using a rapid focus technique will be required. Liquid crystal devices are a possible mechanism which could be used to augment this visual accommodation. It

remains then to consider whether a fast controlled focus is compatible with the physiological control system of the eye and could be used in rapid observation changes.

The theory of eye tracking or saccadic motion is well established and understood as noted in the work of Young and Stark.[2] The problem of importance in obtaining information from moving objects is certainly more involved than this theory. Eye tracking theory is based on obtaining information on only the spatial position of an object in a two-dimensional space. No information is asked about the size, shape or configuration of the object. To include this information, an understanding of the accommodation response of the eye needs to be included. "Tracking for information" could be attacked in several ways:

1. Experiments with an optometer to change the object distance rapidly in order to quantify the physiological response and test an augmentation system.
2. Build a focusing system which has a manually controllable focus for use in tracking an object in space. Then use this to examine the feedback response requirements needed.
3. Provide a system whereby eye lens motion is sensed to control the focus of an augmentated system.

The control questions which must be answered in an automatic focus system or zoom lens control are: (1) What will be the physiological reaction to the automatic control? (2) What conscious response feedback control is present in the focus feedback loop? (3) If a focus system is built with a step-response behavior will this operate more adequately than a continuous focus system?

The use of liquid crystals as a focus control mechanism has an advantage over pressure or lens movement systems because their response time can be much faster since the inertial elements are smaller.

Present research in liquid crystals has been based on observation of effects. The results are in terms of full orientation of molecular groups rather than continuous control of this orientation. The study of the shear-field orientation effect is in part motivated by its potential for continuous control.

The more general applications of the analysis of the action of particles or molecules in flow or in energy fields include the continuous control of liquid slurries in an electrostatic or magnetic clutch or control of the flow of fluids by alternating or direct fields. The applications as field sensors are also numerous and will not be discussed here. (The application to blood flow measurement is discussed in a paper which is in preparation.[3]) The general observation should be made here, however, that emphasis is being

placed on nematic liquid crystals (i.e., those which are vector field sensitive rather than energy or intensity sensitive.)

In the First Progress Report, rough estimates of the change in index of refraction of a lens required to produce an accommodation assist were outlined. A change in focal power of 9 diopters was shown to be adequate for this application. This accommodation could be obtained by altering the radius of curvature or the index of refraction of a lens. The technique of altering the index of refraction was chosen to take advantage of the rapid response possibilities of liquid crystals and their recent availability of room-temperature nematic (shear type) crystals.

Analysis

The index of refraction variation is analyzed by utilizing the relation between index of refraction and dielectric constant

$$n = \left(K \frac{\mu}{\mu_o}\right)^{1/2} \qquad (1)$$

where n is the index of refraction, K the dielectric constant and $\frac{\mu}{\mu_o}$ the relative magnetic permeability. For this analysis the relative permeability is assumed fixed and the dielectric constant effect examined.

The first method of focus control has been the application of a shear field to a nematic type liquid crystal. In order to analyze the index of refraction change possible in

these materials, an analytical model of a liquid crystal as consisting long symmetrical ellipsoids approximating long molecules is assumed. The hydrodynamic effect of a simple shear field on these ellipsoids is then examined. From the motion of the ellipsoids the change in index of refraction is predicted in this section of the report.

As a first approximation, then, long molecules in a fluid will be assumed as ellipsoids with different properties than the fluid in which they are contained. These ellipsoids will be assumed randomly dispersed in a media and free to rotate and translate under the influence of electrical or mechanical forces. The flow geometry of Figure (1) will be assumed with the properties of the fluid designated with subscript "s" and that of the ellipsoids with a subscript "p".

For a random dispersion of ellipsoids (a suspension at rest in the absence of a disturbance) the dielectric constant has been shown[4] to be approximated by the equations

$$K = K_s + \frac{\rho}{3}(K_p - K_s) \sum_{\alpha=a,b,c} \left[\frac{1 + x_\alpha}{x_\alpha + K_p/K_s} \right] \qquad (2)$$

where

$$x_\alpha = \frac{2 - abc\, L_\alpha}{abc\, L_\alpha} \qquad (3)$$

and

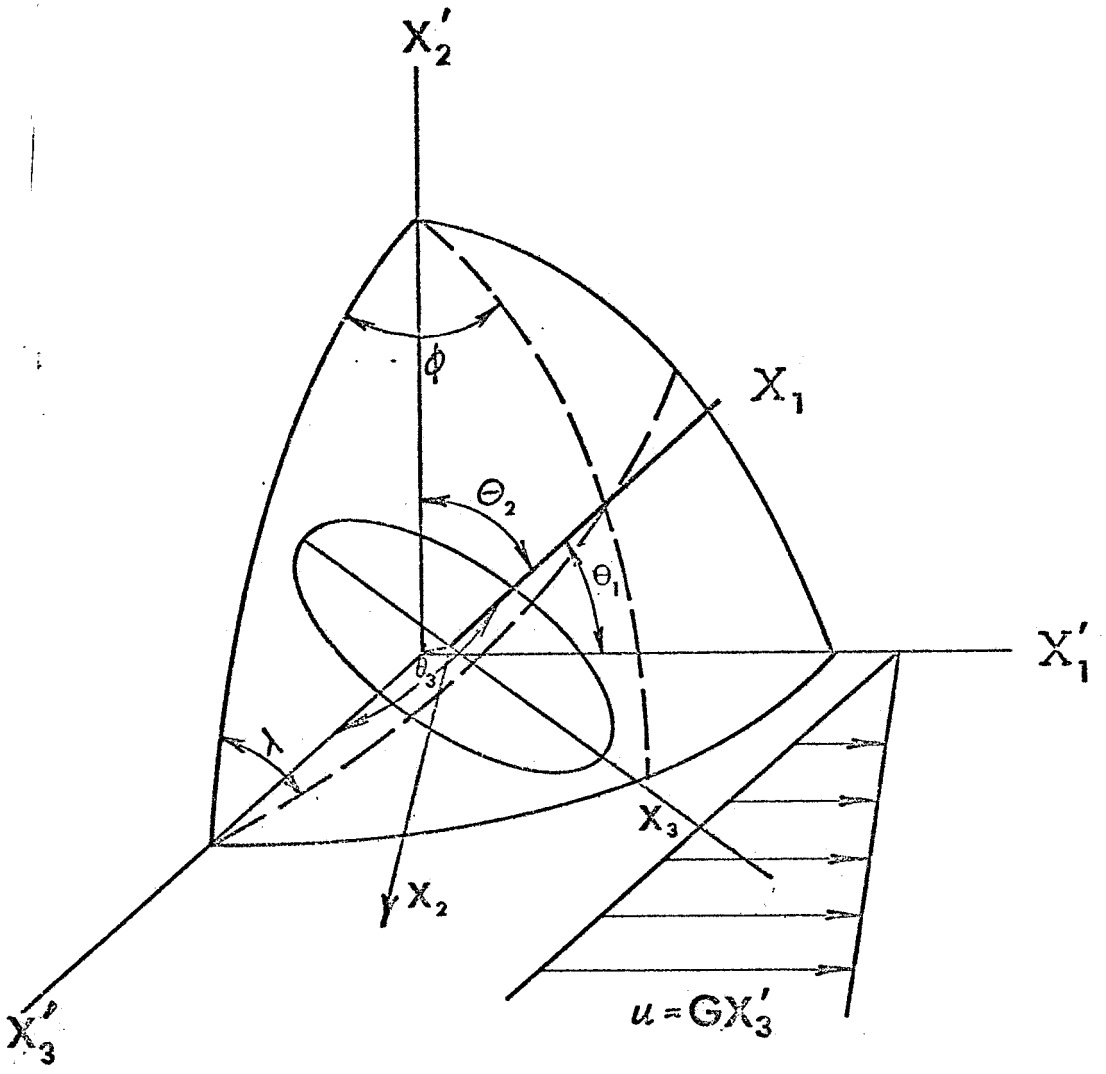

Fig. 1 Coordinate Geometry for an Ellipsoid of Revolution in a Shear Flow

$$L_\alpha = \int_0^\infty \frac{d\lambda}{(\alpha^2+\lambda)\sqrt{a^2+\lambda)(b^2+\lambda)(c^2+\lambda)}} . \qquad (4)$$

((a,b,c,) are the axes of the ellipsoid.)

These equations can be reduced to the dielectric constant for an aligned suspension by replacing $\frac{\rho}{3}$ by ρ and removing the summation sign. For example, to obtain the conductivity of a suspension aligned with the a axes in the direction of the applied field

$$K_a = K_s + (K_p - K_s)\ \rho\left[\frac{1 - x_a}{x_a + K_p/K_s}\right] . \qquad (5)$$

We are concerned in this report with the dielectric constant of a suspension in which the ellipsoids are in motion produced by a field (in particular a simple mechanical shear field).

Similar equations with a replaced by b or c represent the dielectric constant of a solution with the axes b or c aligned with the field. These quantities designated K_a, K_b, and K_c give the principle dielectric constant of a suspension of uniform ellipsoids. The variation of the principle dielectric constants K_a and K_b if the dielectric constant of the particle (K_p) is assumed to be zero is shown in Figure (2) for a particle density of 0.5 as a function of the axis ratio $r = \frac{a}{b}$. To find the dielectric constant at any angle to the principle axes the dielectric constant is assumed to be a second order tensor quality, which transforms according to the tensor relation

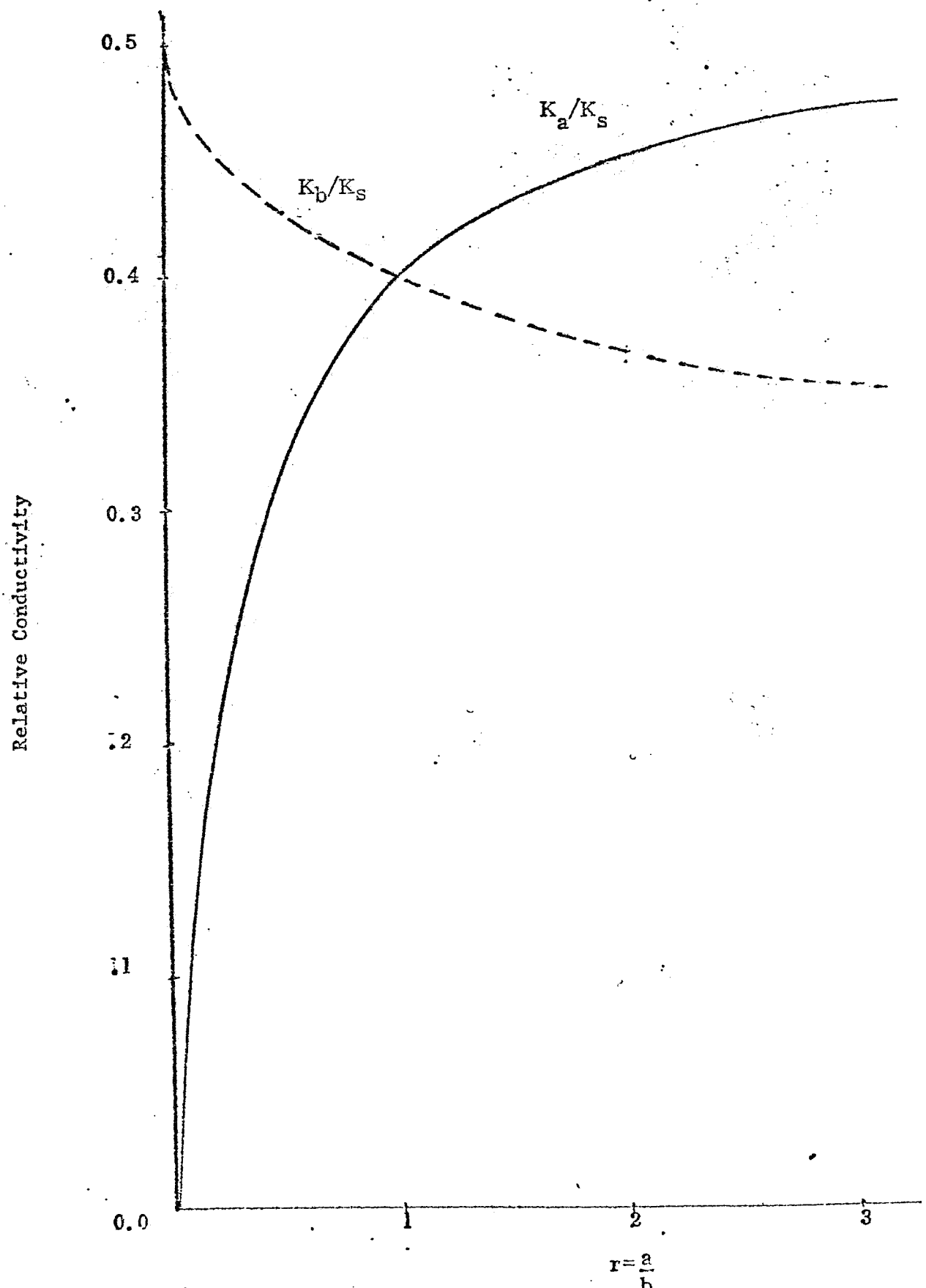

Fig. 2 Theoretical variation of the principal dielectric constant of symmetrical ellipsoids in suspension as a function of the axis ratio r = a/b. The volume density shown is $\zeta = 0.5$.

$$K_{ij}' = a_{ik}\, a_{j\ell}\, K_{k\ell} \ . \qquad (6)$$

$a_{j\ell}$ represent the cosines of the angles between the original axes and the new axes. In this case $a_{j\ell}$ represent the cosines of the angles between the axes of the ellipsoid and the applied field.

Using the tensor property of the conductivity, the conductivity in the direction of the x_3^1 axis is

$$K_{33}^1 = a_{31}a_{31}K_{11} + a_{32}a_{32}K_{22} + a_{33}a_{33}K_{33} \ .$$

Setting $K_{22} = K_{33}$ and using the geometrical relations

$$a_{31}^2 + a_{32}^2 + a_{33}^2 = 1 \ , \qquad (7)$$

and

$$a_{31} = \cos \theta_3$$

then

$$a_{32}^2 + a_{33}^2 = 1 - \cos^2 \theta_3 \ ,$$

and

$$K_{33}^1 = K_a \cos^2 \theta_3 + K_b(1 - \cos^2 \theta_3) \ . \qquad (8,a)$$

Similarly

$$K_{22}^{1} = K_a \cos^2 \theta_2 + K_b(1 - \cos^2 \theta_2) \qquad (8,b)$$

and

$$K_{11}^{1} = K_a \cos^2 \theta_1 + K_b(1 - \cos^2 \theta_1) \ . \qquad (8,c)$$

These three equations define the dielectric constant of a suspension in which the electric field is in the direction of one of the prime axes in terms of the principle dielectric constants and the cosine of the angle between the axis of symmetry and the direction of the field.

The dielectric constant is then obtained by proper averaging as a function of angle of the ellipsoids to the applied electric field. (See Appendix III.)

The results of this analysis may be summarized by the following discussion and equations.

The dielectric constant of a sheared suspension in the three directions x_1', x_2', x_3' may be represented by the equations

$$\overline{K_{11}'} = K_b + (K_a - K_b)\ \overline{F_1} \qquad (9,a)$$

$$\overline{K_{22}'} = K_b + (K_a - K_b)\ \overline{F_2} \qquad (9,b)$$

$$\overline{K_{33}'} = K_b + (K_a - K_b)\ \overline{F_3} \qquad (9,c)$$

The variation which can be produced by a shear field is summarized in Figure (3) where the shear factors F_1, F_2 and F_3 are shown as a function of the ellipsoidal axis ratio, r.

Since the factor F is 0.5 (Equation A5, Appendix A) when the suspension is randomly orientated (i.e., when the suspension is dispersed due to Brownian motion), the variation from this value with shear represents the magnitude of the effect. If we are concerned with long molecules (prolate ellipsoids) where $r >> 1$ it is clear that slight variation with shear occurs in the direction perpendicular to shear planes ($\overline{F_3}$). The maximum variation occurs along the shear planes in the direction of the shear (F_1). For control of properties by a shear field the maximum response can be obtained (for $r >> 1$) by motion in the x_1^1 direction and observation in the same direction. If the control is provided by a sandwich the plates should be moved parallel to each other and the observation made as shown in Figure (4,a). The other alternative is to vibrate a plane perpendicular to the sandwich and observe as whown in Figure (4,b). If we are concerned with a fluid with oblate particles [(or discs with ($r << 1$)], then the response will depend upon the direction of observation. The effect is much greater for observation in the x_3 and x_2 directions than for prolate spheroids. If a choice of form of the particles is possible then oblate spheroids have a clear advantage from the control or detection point of view. For liquid crystals we do not have this choice, the molecules are approximated by long prolate

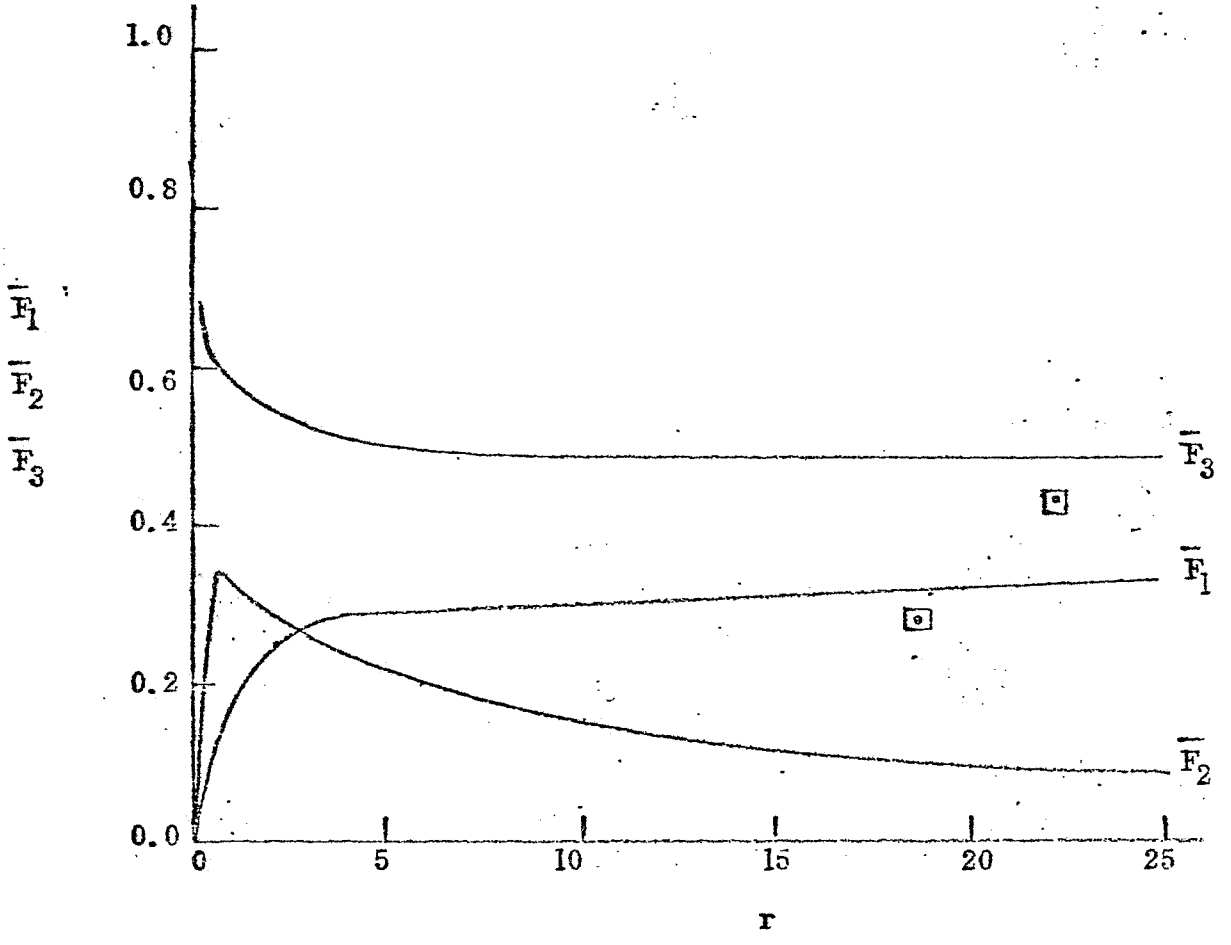

Fig. 3 Computed theoretical conductivity factors for conductivity as a function of the ellipsoid axis ratio r = a/b.

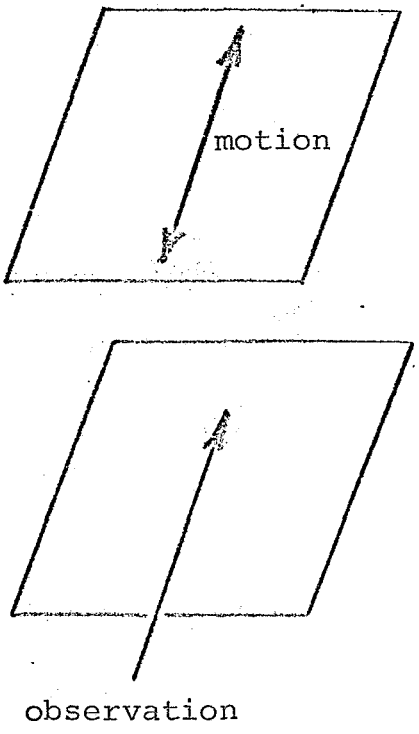

Figure 4a

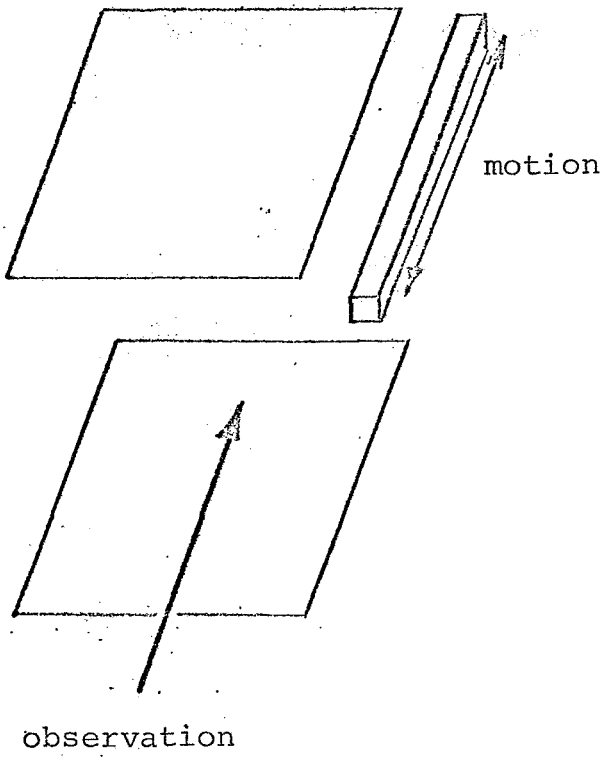

Figure 4b

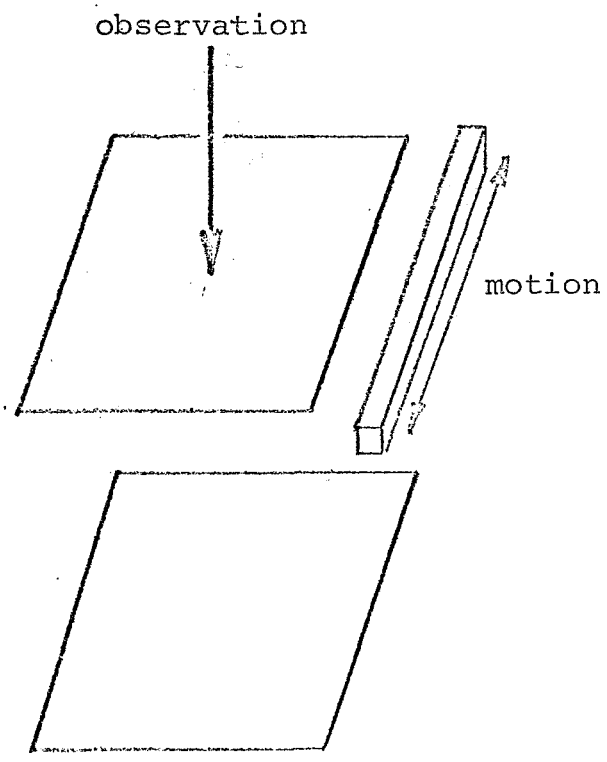

Figure 5

ellipsoids. In this case the best alternative at present is the system shown in Figure (5).

Experiments-Observations on Corneal Transparency

The incidental problem of corneal transparency which is important in the context of fibrous material transparency has been examined further with some physiological exploratory experiments.

Excised rabbit cornea have been examined in the laboratory for determination of their scattering properties. From observations with polarized laser light, it is observed that scattering from particles greater than the size of the fibrils involved is appreciable (using techniques of crossed polarizer transmission). The scattering has been difficult to quantitate because of the rapid deterioration of these cornea in saline solution. By the use of crossed polarizers, it has been estimated in preliminary experiments that the ratio of the intensity transmitted to scattered light by the cornea is approximately 10 to 1. These are preliminary data and improvement in experimental technique will be required to describe this more accurately.

These experiments are directed toward the understanding of the transparency of the cornea and its relation to the transparency of orientated fiber type materials. The relation of this work to liquid crystals was discussed briefly in the First Progress Report.

Summary

The theoretical analysis of the effect of a shear field on a suspension of long ellipsoids (representing a nematic liquid crystal) has been completed. The dielectric constant and index of refraction changes to be expected have been estimated. The other two steps outlined in the First Progress Report are now to be attempted.

1. Experimental demonstration of control of index of refraction by a shear field including flat and cylindrical configurations.
2. Further work on corneal transparency is in progress including scattering from corneal fibrils. In addition, an extension to focus or accommodation control is expected as explained briefly in the beginning of this section.